

Helium and Pressure Susceptibility of Components used in Electronic Systems

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A	2 nd Feb 2006	Blue Book Initiation for saturation diving application
B2	16 th Aug 2010	Section issued as part of Blue Book and extracted from that to form this document. Updated with long term results Dec 2006, to form B1. Updated with CO sensor data, to form B2.

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Table of Contents

1	PURPOSE AND SCOPE.....	3
2	EQUIPMENT USED:	3
3	REFINING THE DESIGN OF THE TEST	4
3.1	Design and Fabrication of Pressure Vessel and PCB.....	4
3.2	Choice of components.....	4
3.3	Method for Metastability measurements.....	6
3.4	Method of CMOS inverter characterisation	8
4	RESULTS	11
4.1	Passive components.	11
4.2	Resonators	11
4.3	Integrated Circuits.....	12
4.4	Piezo Buzzers.....	14
4.5	Pressure Sensors	14
4.6	Fibre Reinforced Housings	14
4.7	Oxygen Sensors	14
4.8	Lithium Ion Cells	14
4.9	Mylar Film Speakers	14
4.10	Microphones.....	14
4.11	Pressure Cycling	15
4.12	IR Source and IR Sensor.....	15
4.13	Carbon Monoxide Sensor.....	15
5	MECHANISMS OF HELIUM MIGRATION.....	15
6	CONCLUSIONS	16

1 PURPOSE AND SCOPE

The purpose of this study is to determine the extent to which component types used diving equipment are subject to accelerated failure when exposed to helium under pressure, and to identify any types used that are liable to be damaged by fast pressurisation cycles. Pressures to 143 bar were used, and soak periods of up to 700 hours.

The component types tested are

- SMT Capacitors, ceramic, nominally 0.1uF
- SMT Capacitors, tantalum, nominally 100uF
- Leaded Ceramic Resonator nominal frequency 8MHz
- SMT resistors, 100KOhm
- CMOS inverters: 74HC02 with RC generating 2.8MHz and data RC 387KHz
- CMOS latch: The M74HC273 is a high speed CMOS OCTAL D-TYPE FLIP FLOP WITH CLEAR
- Li ion gel batteries ICR188650S2
- IR source
- O2 sensor Teledyne R22-2BUD2 and Analytical Industries PSR-11-39-MD
- Piezo components: buzzers and mics
- Moving coil buzzers and mics
- Pressure sensors of piezo resistive, strain gauge, capacitive and MEMs construction.
- Carbon Monoxide Sensor

The scope of this work is a verification report prepared in accord with Quality Procedure QP-20, for safety critical systems.

2 EQUIPMENT USED:

Measurements were made using instruments that are, or are among, the highest precision lab instruments that are commercially available:

1. Capacitance : TIME ELECTRONICS 5075 8.5 DIGIT PRECISION METER. s/n: 1234J04
2. Resistance: TIME ELECTRONICS 5075 8.5 DIGIT PRECISION METER. s/n: 1234J04
3. Frequency: HEWLET PACKARD 1663CS LOGIC ANALYZER s/n: US37040105 and TDS8000 below for high precision
4. Metastability: TEKTRONIX TDS 8000 50GHZ DIGITAL OSCILLOSCOPE.s/n: B010581
SAMPLING MODULE 80E04 20GHZ CH4 B011019
TEKTRONIX P6209 4.0 GHz ACTIVE FET PROBE s/n: B010398
TEKTRONIX P6209 4.0 GHz ACTIVE FET PROBE s/n: B010478
5. Power supply: ISO-TECH IPS3 02A s/n: 9201346

The Supply voltage was 2.30751V.

Environment temperature (during measurement after test) was 23C.

The pressure gauge used was not instrument grade, but of 3% accuracy and linearity. The reason a more accurate gauges was not used is simply because the variations in pressure due to changes in temperature with pressurisation and depressurisation is more than 3%, and the margins used in the test are 100% higher than the maximum pressure that would be experienced in the field.

3 REFINING THE DESIGN OF THE TEST

After defining what components to test, the Review Team considered four questions:

1. **What Pressure?** A review of this question concluded that the test should be carried out at twice the maximum He pressure that could be applied – this is the same margin of safety that is applied to a pressure vessel. For operation at the deepest depth ever dived (701m, dry in the COMEX facility by a Greek diver), this means 142 bar. The test was actually carried out at 143 bar. Increasing He pressure beyond all sensible limits would simply put undue pressure on components and the results would not indicate anything: at some pressure, all components will fail.
2. **For how long?** The longest period the rebreather would be used is 9 hours. After that it is returned to the surface. During this time it would depressurise. He builds up in the devices under test is similar to tissue saturation: it is an exponential asymptotic increase. The tissue half-life of the components is not known, but it was decided to provide a 350 hour test. This exceeds the maximum operational period of exposure of any component by a large margin. This also covers the case where equipment is left in a saturation diving environment for the duration of the saturation period: critical components such as pressure sensors are tested for 700 hours under pressure.
3. **How many components should be tested?** The Review Team considered that the purpose of the test was to indicate whether components had a generic failure under pressure in helium, therefore it was not necessary to test a large batch. A batch of one would be sufficient, though two sets of circuit boards and chambers were made, in case there was a failure in one that affected the ability to continue the test.
4. **How many pressurisation cycles?** In service, components would be pressurised slowly, so to provide a suitable margin, components were pressurised and depressurised within 3 seconds. That is, pressurised from 1 ATM to 143 ATM in 3 seconds, left there for a soak period of several hours, and depressurised again in 3 seconds. 50 such cycles were deemed sufficient to show whether there was a generic failure mode in rapid pressurisation.

3.1 Design and Fabrication of Pressure Vessel and PCB

A dive cylinder or gas cylinder cannot be pressurised or depressurised as fast as required to test the component for pressurisation cycles, even with hydraulic filling, so a special test micro test chamber was designed and built for this test.

The pressure chamber was fabricated with the HP connection for both a J cylinder and a HP port on a regulator. These connections can be swapped (they screw into the chamber). The entire assembly is shown in Fig 3-1. Prior to the exposure test, the components were submitted to 50 3-second pressurisation/depressurisation cycles, as described above.

To make very accurate measurements on components, it is important that the wiring and construction are robust. For that reason, rather than use prototyping board (Veroboard), a printed circuit board was designed and fabricated for the test. After the pressurisation tests, the components were mounted on the pcb, then placed inside the pressure chamber. The pressure chamber was then connected directly to a J cylinder of helium at 143 bar and pressurised rapidly (within a few seconds). The pcb was left in the helium under pressure for 350 hours, then depressurised within a few seconds, removed from the pressure chamber and recharacterised.

3.2 Choice of components

Components in the REBREATHER operate under different levels of He exposure. There are three categories:

1. Components maintained at 1ATM. These include the batteries, and the IR sensor. The reason for 1 ATM in each case is that consideration of their construction shows there is a risk of catastrophic failure if they are pressurised. Failure of the IR sensor would not be critical to the

REBREATHER, but batteries are classed as critical, so are housed in such a way that there is no risk whatsoever of gas leaking into their housing.

2. Components at ambient, but hermetically isolated from the breathing gas. This applies to almost all components. This case is considered in detail below.
3. Components in the breathing loop, operating at ambient pressure. Very few components are in this category. The present test assesses their sensitivity to He.

Some components from each category above are included in this test, and all component types in Category 3 that are used in the REBREATHER.

Category 2 components are in silicone oil in a hermetic chamber, exposed to the ambient sea water on all but one side. That side is separated from the breathing loop by an MS 6 stainless steel plate, with sections for connectors machined into the plate and backfilled with epoxy resin. The silicone oil is at close to ambient pressure because the plastic housing deforms slightly under pressure to compress the silicone oil (0.2%). The partial pressure of helium on the electronic components is very low under these circumstances. For this reason, no penalty is assumed in MTBF calculations for helium diffusing into the components.

However, it is possible for helium to leak slowly into the hermetic volume. The maximum pressure of helium would be 1 bar, as above this the hermetic chamber would rupture. This test accelerates the effect of the 1 bar of He by subjecting the components to 143 bar of pressure. Sensitive characteristics of the components are measured before and after exposure to helium.

Each hour of exposure at 143 bar, for a Category 2 component, is equivalent to 143 hours at 1 bar. The test examines the parts after the equivalent of 150 hours. The table below shows the hours of equivalent exposure each time the components are characterised.

Elapsed Hours	Category 2 Component Equivalent Hours when under 150 bar He pressure
1	150
12	1,800
72	10,800
168	25,200
504	75,600

The buzzers and mics were simply tested for function and any change in tone noted.

Two test chambers were built, and three circuit boards (reference, two samples).

Capacitors, resistors and other passives were characterised for value using the Time Electronics precision meter: this is an 8.5 digit instrument with highest available commercial accuracy.

The CMOS inverters were characterised by being connected into a ring oscillator on the circuit board and the frequency measured using the auto-measurement facility of the oscilloscope (an ultra high performance 50GHz mainframe oscilloscope). The fact that a ceramic resonator is used means that the HP1663 has ample accuracy for the measurement, and was used to report results.

The CMOS latch was characterised for metastability: this is the distribution of switching probability for a particular clock to data delay. Metastability characteristics are extremely sensitive. This device test would reveal any change in: rise and fall times; the Ft of the transistors; circuit elements in the device. All metastability measurements were taken using the TDS8000 50GHz mainframe.



Fig 3-1: Pressure Chamber designed and fabricated for He susceptibility test, with test pcs. Shown screwed into the HP port of a regulator for first cycle tests.

3.3 Method for Metastability measurements

The method used to measure metastability was as follows:

A random CLK and DATA to obtain random setup and hold times with a continuous distribution. This produces a distribution of transition points such as shown below:

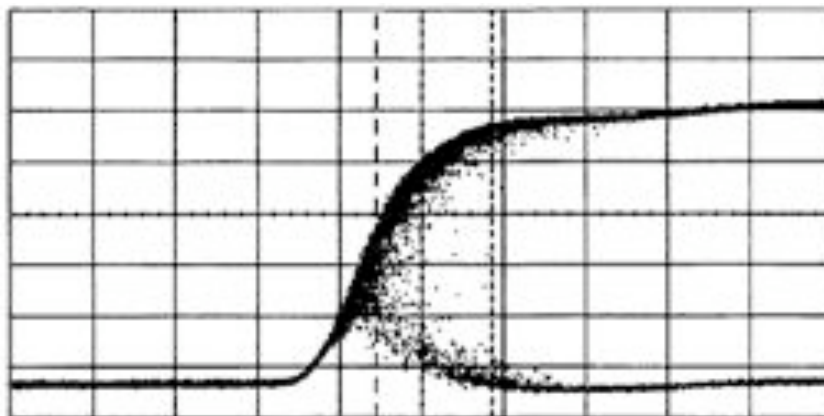


Fig 3-2: Metastability of rising edge (clock to data)

From this, the minimum and maximum Propagation Delay Time (CLOCK - Q) and the width of the distribution are calculated. (Sigma of the distribution is measured directly by the measurement function of the oscilloscope). The figures before and after the effect of He are then compared.

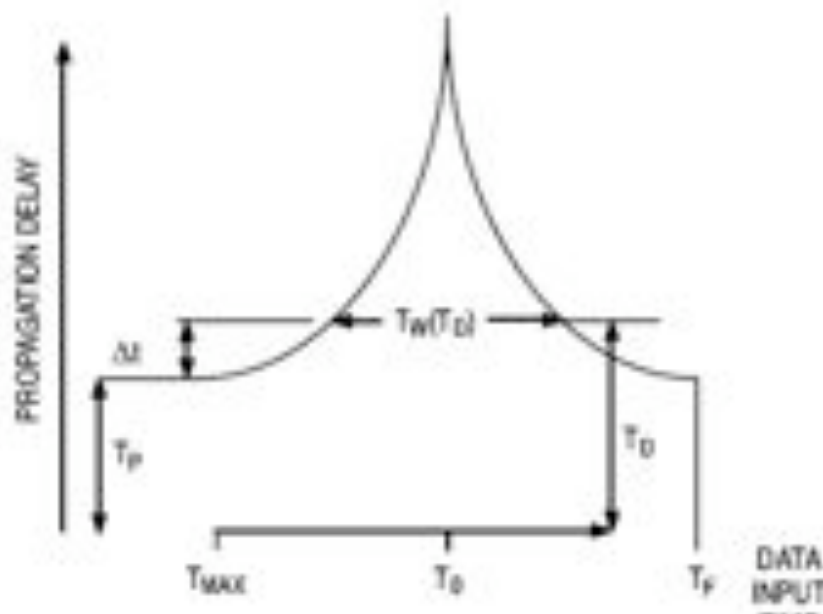


Fig 3-3: Distribution of transitions

More information is available on

http://www.eetkorea.com/ARTICLES/2004MAY/2004MAY18_AMD_AN.PDF

Care was taken to make all measurements at the same temperature: within 1C of 23C.

Looking at datasheet of flip flop M74HC273 :

<http://pdf.alldatasheet.com/datasheet-pdf/view/23065/STMICROELECTRONICS/M74HC273.html>

we find that Minimum Set-up Time = 95ns

Minimum Hold Time = 0ns

The CLK period should be more than (Minimum Set-up Time + Minimum Hold Time) i.e. frequency less than 10 MHz.

The value of RC CMOS oscillator jitter can be taken from :

<http://comscire.com/Products/PCQNG20/HCalc.aspx> but was found to be 7×10^{-6} times the period. The jitter of DATA should be approximately equal to the period of CLK. For example, if CLK frequency = 5MHz then DATA frequency should be = 35KHz. Following this calculation, it was decided to increase the CLK frequency and decrease DATA frequency: that is the 700Khz - CLOCK and 14Khz - DATA: they were increased to 2.8MHz and 360KHz respectively.

For ease of measurement, the metastability plots for both edge transitions were overlaid: Fig 3-4 shows a typical result. The circuit is shown in Fig 3-6.

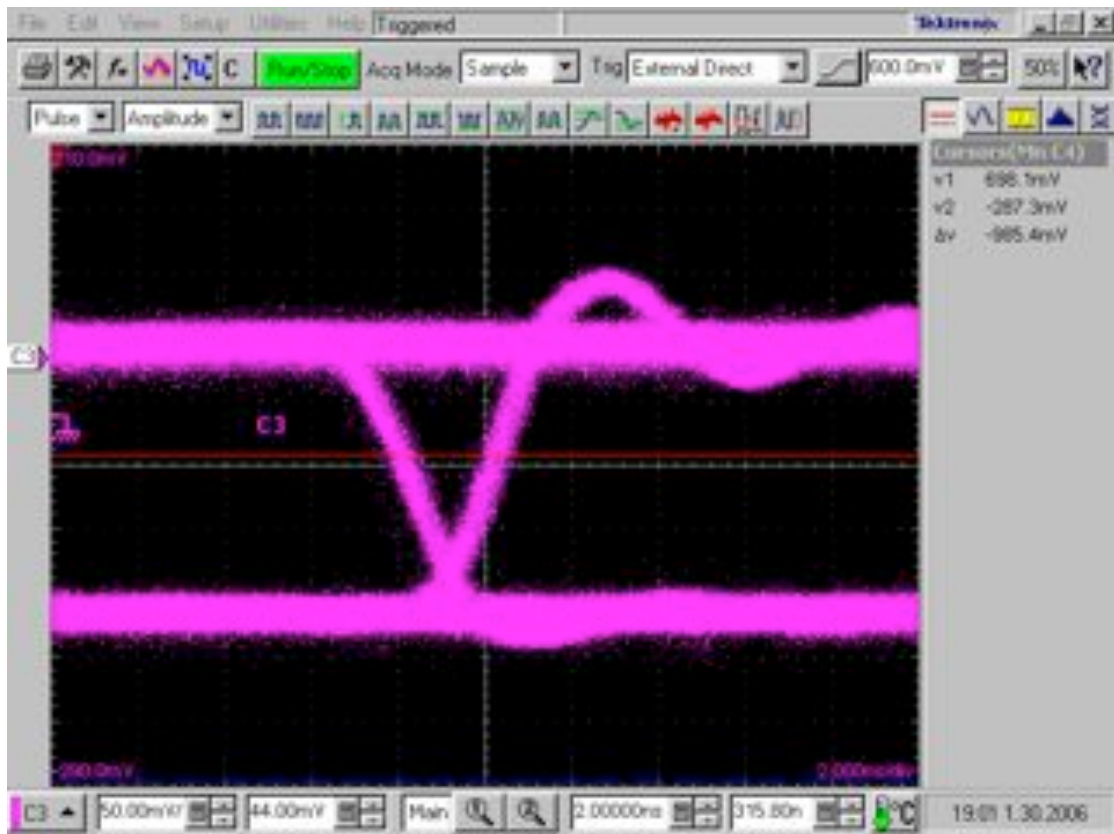


Fig 3-4: Plot on TDS8000 showing metastability curve measured during test.

For completeness, the entire set of metastability curves, showing those at the beginning of the test (before any He exposure) and at the end of the test, is shown in the results reported below.

3.4 Method of CMOS inverter characterisation

The inverters were formed into a ring oscillator by connecting an odd number of stages into a loop. The frequency of the loop will vary if the inverter stages vary, as will the jitter of the transitions.

The He influence measurement was made with a PCB test bench. The circuit is shown in Fig 3-5.

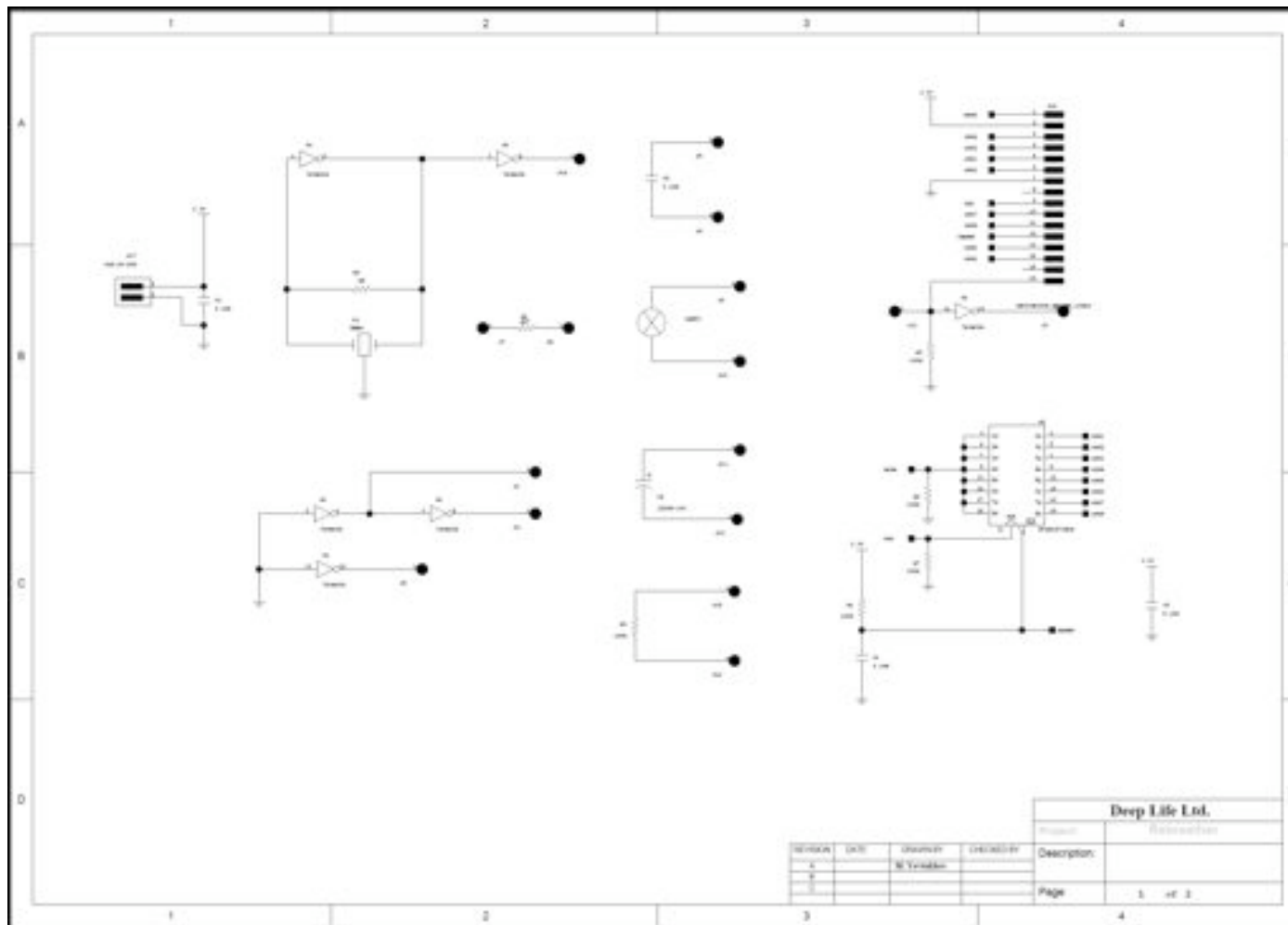


Fig 3-5: Leakage test PCB.

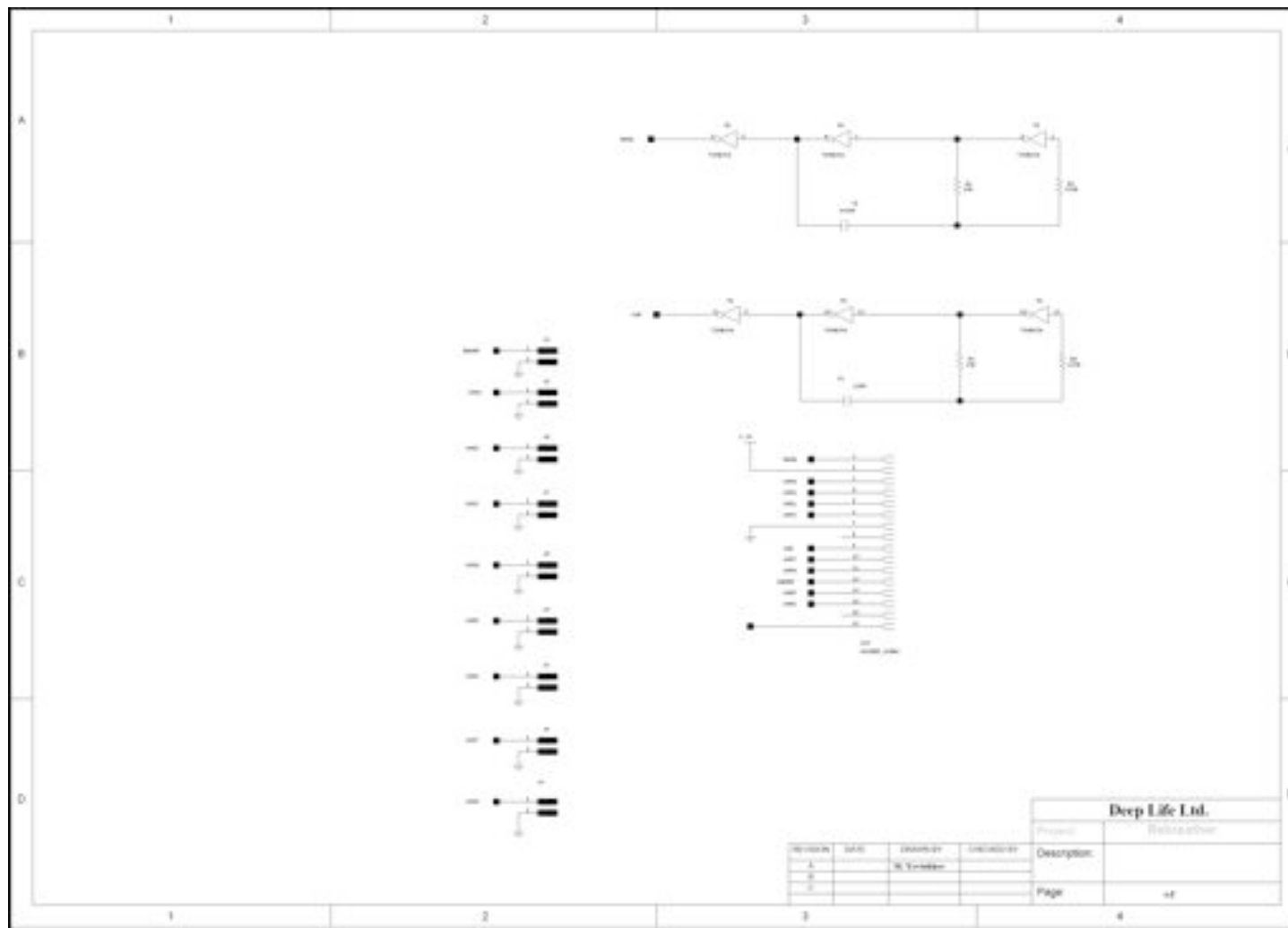


Fig 3-6: Metastability test PCB.

4 RESULTS

4.1 Passive components.

No change in any passive component was observed, other than changes due to slight differences in temperature and ageing of the component. Actual measurements are tabulated below.

The tantalum capacitor was physically deformed by the test,

	Before He Test	After 1 hour	After 22 hours	After 2 weeks
C2	111.61nF	111.15nF	110.40nF	108.60F
C4	101.01uF	101.09uF	100.73uF	100.99uF
R3	100.761kOhm	100.7582kOhm	100.75kOhm	100.739kOhm

4.2 Resonators

The clock oscillator was characterised for frequency, and for rise and fall times. The results are shown below. There is no indication of any change as a result of helium exposure.

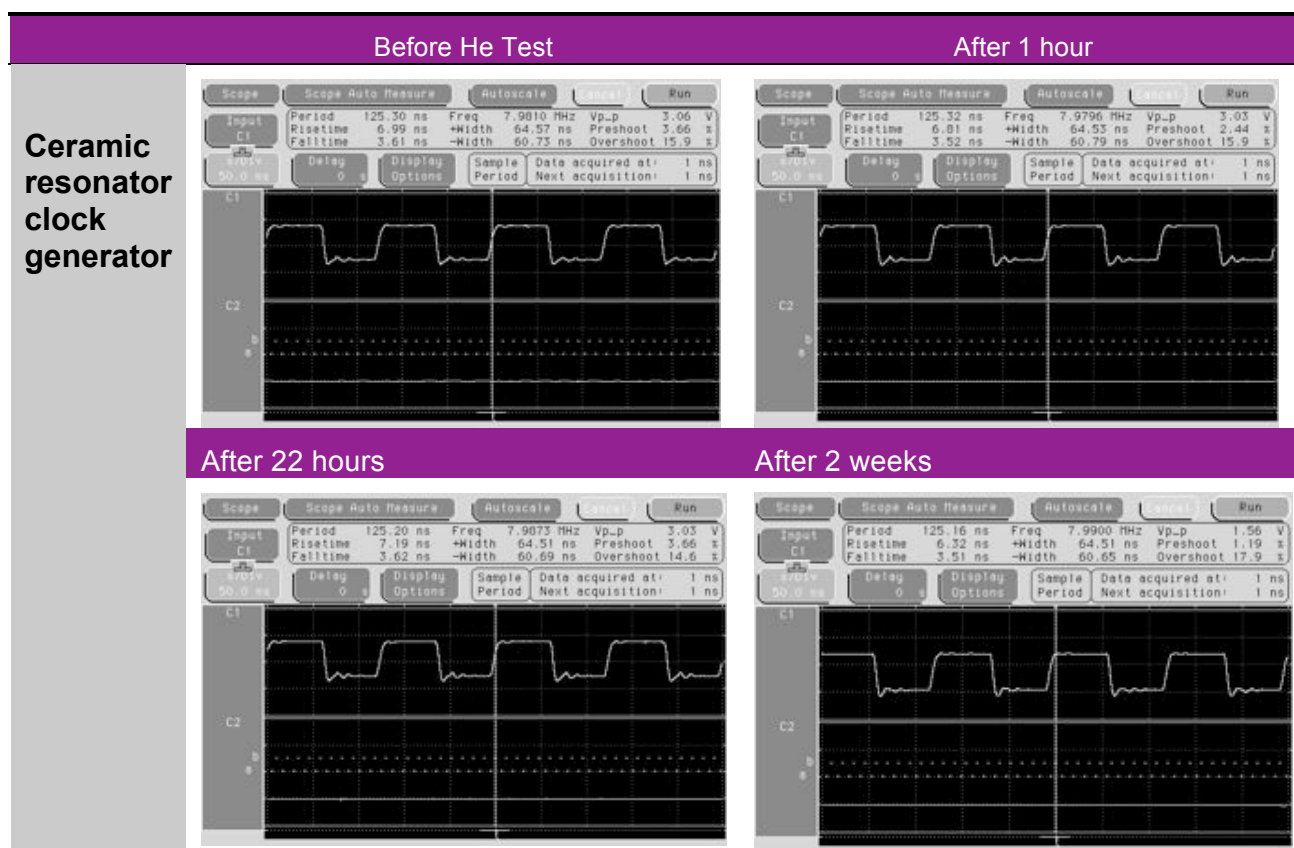


Fig 4-1: Clock oscillator under helium pressure soak

		Before He Test	After 22 hours	After 2 weeks
Clock Output Time (Fall)	min	24 ns	24.08 ns	24.16ns
	mean	24.20 ns	24.22 ns	24.30ns
	RMS	94.44 ps	94.46 ps	113ps

4.3 Integrated Circuits

The metastability results are shown below, taken directly from the TDS8000. There is no indication of any change due to the effect of helium.

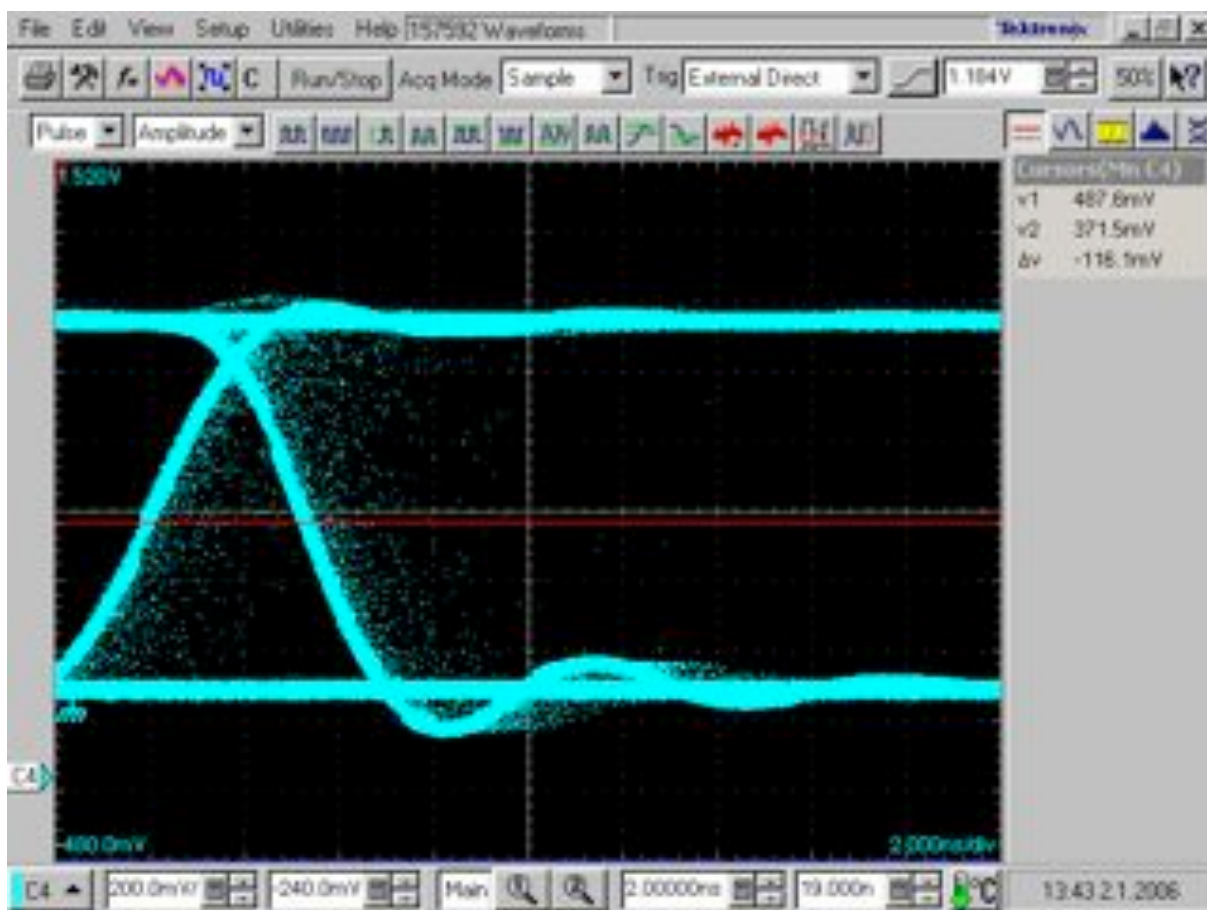


Fig 4-2: M74HC273 Q4 Output Before He Test

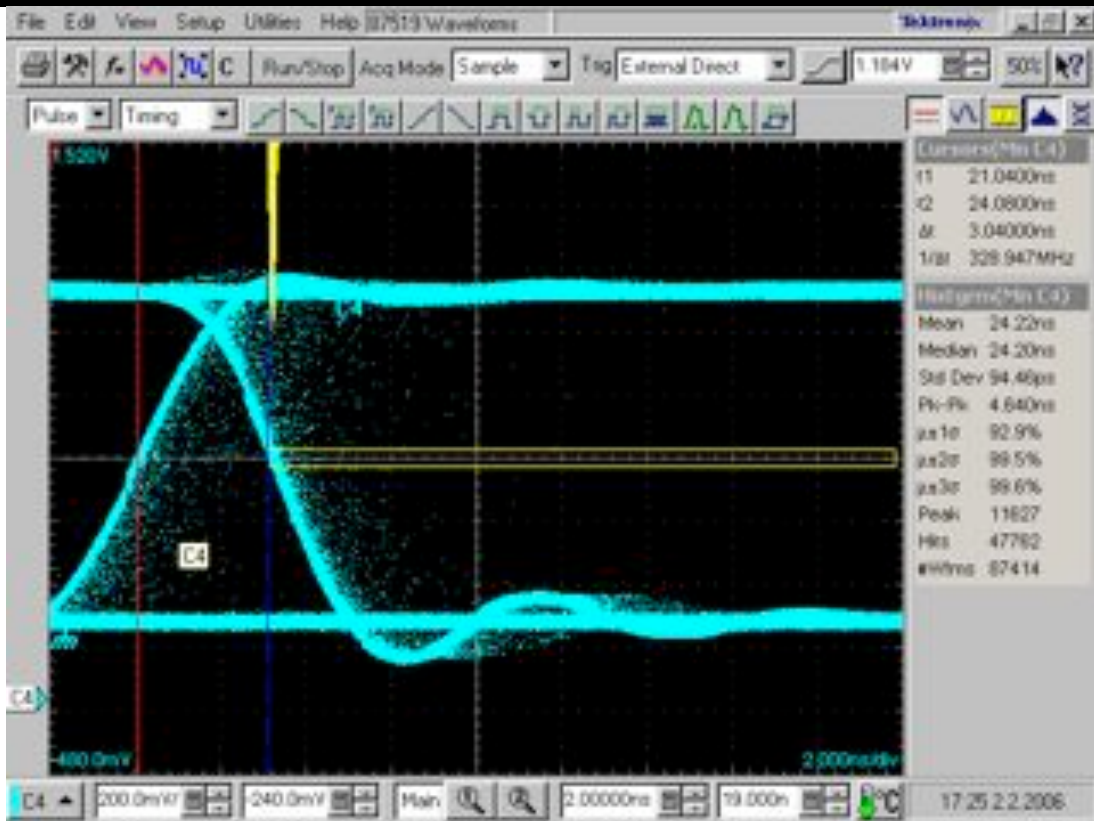


Fig 4-3: After He Test (22 hours)

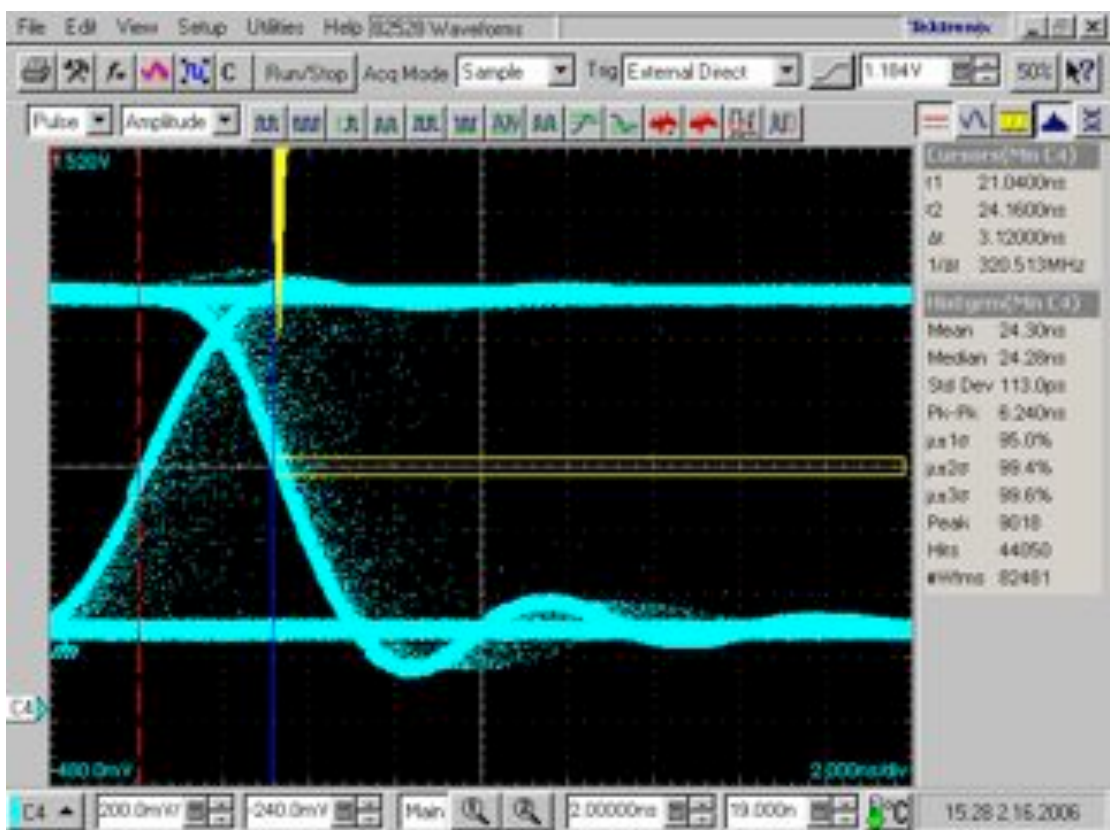


Fig 4-4: After 2 weeks

4.4 Piezo Buzzers

Piezo components fail almost immediately when exposed to helium under pressure. This is also the experience in the field: microphones used in commercial diving fail within hours at pressures far less than tested here.

4.5 Pressure Sensors

Pressure sensors were all found to creep under exposure to helium.

Many different pressure sensors were measured, including pressure sensors where the rear face is pressurised using silicone oil. All sensors exhibited creep, with errors of up to 8 bar.

4.6 Fibre Reinforced Housings

Whilst not related to He susceptibility, it is appropriate to deal here with one other component which is affected by pressure: housings made from fibre-reinforced materials.

4.7 Oxygen Sensors

A separate report contains details of the oxygen sensor testing. Multiple sensors were tested. In brief, the sensors are tolerant of pressure but are not tolerant of fast pressurisation or depressurisation: the manufacturer advises they should be decompressed at the same rate as a human. Instant decompression caused the output of the sensors to change, and for the sensors to not respond to oxygen in a linear fashion, until they had decompressed fully: this recovery period lasts several days.

4.8 Lithium Ion Cells

Four different makes of cell were tested. One of these was a non gel cells batteries in a hermetic can were ruptured by the rapid pressure changes: the result was the battery leaked. The battery terminal voltage was not affected (3.81V) but after leaking, the battery could supply only a few tens of mA and would not charge.

Gel cells seem to be more tolerant of pressure changes, but changed their characteristics (voltage, current capability) after pressurisation. It is noted these cells are both an off-gasing hazard and an explosion hazard so are not suitable for pressurisation.

For safety, batteries are kept at 1ATM in all Deep Life RB controllers, with no possibility of He leakage

4.9 Mylar Film Speakers

Mylar film speakers gradually changed their response when soaked in helium.

Polyimide film speakers did not change their response when soaked in helium,

4.10 Microphones

All microphones that were tested failed or changed their characteristics in helium except for silicon micro machined (MEMS) microphones and a Russian military noise rejecting microphone.

A more complex setup was used to test the microphones under pressure. After speakers were identified that did not change their characteristics, the microphones were tested for frequency response under pressure. It was found that the sensitivity of microphones increases linearly with pressure, so at 61 bar, the microphone is roughly 60 times more sensitive than at 1 ATM. This requires the microphone sampling circuits to handle a very wide dynamic range.

The MEMs microphone was soak tested in pure helium at 143 bar for a month, without deterioration. However subsequent dive trials found the MEMs microphone was destroyed with moisture.

The Russian noise rejecting microphone both withstood helium and wet environments. It was also highly tolerant to shock and mishandling. This microphone was adopted, with the signal improved by companding and filtering.

Further investigation found that moving coil microphones appear to be generally tolerant of helium.

4.11 Pressure Cycling

All components that were unaffected by one pressure cycle, were unaffected by further pressure cycling.

4.12 IR Source and IR Sensor

The IR sensor is used to detect CO₂, CO and HC.

The IR sensor has delicate windows on it, and clearly needs to be protected from the effects of pressure. A sapphire window is used for this. If the seal on that window fails, or the seal behind the seal fails, then the entire IR sensor fails.

The thermal properties of the IR emitter changes with pressure due to the conduction of the gas. The emitter is a silicon micro machined component. There is no damage to the emitter up to the pressures tested, 143 bar, but the change in response must be compensated by calibration.

4.13 Carbon Monoxide Sensor

Four CO sensors were tested: all use a heated element coated with a catalytic material that changes its resistance in the presence of CO and Volatile Organic Compounds (VOCs).

The CO sensor AS-MLC from Applied Sensor did not function as described in the data sheet under any conditions. Attempts to contact the company met with a stone wall: the sensor does not work as described.

Three other sensors were examined. All failed to reach the operating temperature in helium, so failed to detect CO in Heliox environments.

A technology developed by Aktina Ltd, a spin out from the University of Dundee, appears to operate in a high helium environment provided the catalytic temperature of 200C can be achieved.

5 MECHANISMS OF HELIUM MIGRATION

The mechanisms by which helium migrates into components was studied. It was found that helium migrates along stress lines. This can be demonstrated most forcefully with a helium party balloon. After an initial fill with helium, after a few days it loses enough helium not to float, and in a week is flat. Spraying a thin layer of silicone flexible lacquer over the balloon after it has been filled, allows the balloon to float for more than a month. The very thin lacquer prevents the helium leaking much more than the thick rubber of the helium balloon. The helium still leaks out, because of changes in temperature and ambient pressure create a strain on the lacquer, but the point is that when the material is under stress helium pours through it, but when not under stress it diffuses very slowly. The difference in diffusion rates is more than four orders of magnitude.

To avoid the effects of helium migration on pressure sensors, the pressure sensor can be placed in the silicone oil that protects the electronics from uneven strain due to pressure. The wall between the electronics and the breathing loop, and the ambient, is not under strain because the silicone oil is at ambient: there is a piston to take up changes in volume due to expansion and contraction of the oil that is vented to the ambient environment.

This same silicone oil protects the crystal oscillators from helium. During the tests carried out here, those oscillators did not fail because they were well sealed: the package is tested by the manufacturer for helium migration and the rate is less than 10⁻⁸ bar per hour when in helium at 1 ATM. It is hazardous to rely on that sealing: the oscillators should be shielded from the helium in the same manner as the pressure sensors.

6 CONCLUSIONS

There is no problem with He diffusion into any of the components used in the rebreather, except for the O2 sensor, where the compression and decompression rates must be limited.

The overall result of the test is as follows:

- SMT Capacitors, ceramic were not affected.
- SMT Capacitors, tantalum were not affected, but from their construction it is clear tantalum capacitors are stressed by being pressurised. The housing of the capacitors were deformed by the test. Tantalum capacitors fail short circuit 90% of the time, increasing their risk. It is concluded that tantalum capacitors are unsuitable for a safety critical system that operates under pressure.
- Ceramic resonator were not affected.
- SMT resistors were not affected
- CMOS inverters. Not affected either in frequency of the ring oscillator or the jitter profile.
- CMOS latch. Not affected – no change in jitter, metastability profile or edge shape.
- Li ion gel batteries. Non gel cells fail under pressure. Gel cells are more tolerant, but the off-gassing hazard and explosion hazard remains. These cells must be kept at 1 ATM .
- IR source. Components will be screened for leakage in production. Properly manufactured IR sources are not He susceptible, but by examination of their construction it is apparent that a faulty IR source will fail faster in He under pressure than in air at 1 ATM.
- O2 sensor. No problem if pressurised and depressurised slowly. Fast depressurisation causes bubbles in the electrolyte. Deep Life will provide a depressurisation schedule for these with the design. The effects of fast depressurisation are generally reversible.
- Piezo components. A piezo buzzer and a piezo mic were tested. As expected, both failed within an hour (143 hours equivalent elapsed time), and were withdrawn from the test. No piezo components are used in the REBREATHER, but StatOil reported piezo microphones as failing rapidly in He, and the test result confirms that.
- Mylar film (moving coil) buzzers and mics are affected by He, except for polyimide speakers and MEMs microphones.
- Carbon Monoxide sensors using a heated element do not function at all in helium under pressure, due to the heat losses.
- Moving coil microphones are not affected by He.

There were small differences in component values during the test, but these are similar to those caused by ageing or slight temperature differences rather than anything affecting the operation of the component.

The failure of piezo components is of special concern. There appears to be an unreported physical phenomenon, where helium interacts with piezo materials, attenuating their piezo effect. It is vital that these are not exposed to helium. A method of protecting these components from helium is described, which is effective at preventing damage from helium. The components are still subject to pressure.

Integrated circuits tested were in lead frame packages. BGA packages are entirely unsuitable for equipment that is pressurised: any strain on the circuit board will fracture the ball bonds under the package, and may fracture the micro balls between the die and the carrier. All integrated circuits should be checked to ensure they do not use flip chip bonding of the die to the carrier.